Efficient data fusion using wavelet transform: the case of SPOT satellite images

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ABSTRACT

A way of increasing the spatial resolution of SPOT multispectral images (XS) using the corresponding panchromatic image (P) is presented here. Existing methods for merging P and XS are analysed, before presenting a new method which aims at simulating 10 m resolution multispectral images that contain the same spectral information as the XS images. This method, called ARSIS after its French name "Amélioration de la Résolution Spatiale par Injection de Structures", is based upon multiresolution analysis and wavelet transform. Different versions have been implemented, which differ on the model that describes the similarity of the spatial variability of P and XS. ARSIS can also be applied to other sensors, featuring different spectral bands and spatial resolutions.

1. INTRODUCTION

Remote sensing data flowing down from earth observation satellites are routinely processed all over the world, to produce maps and to help improving the knowledge of our changing environment. The SPOT satellites are a major component of this earth observation spatial network. These satellites carry an optical instrument which measures the radiances of Earth objects in three spectral bands : XS1 (green 0.5-0.6 µm), XS2 (red 0.6-0.7 µm), XS3 (infrared 0.8-0.9 µm), with a spatial resolution of 20 m. The SPOT instrument also comprises a panchromatic band P of low spectral resolution (0.5-0.7 µm) but high spatial resolution: 10 m.

Many remote sensing applications emerge, which require both the high spatial resolution and the high spectral resolution. Attempts have already been made to merge P and XS data, but all the resulting methods strongly alter the radiometry of XS images. These methods can be separated into two classes : those which combine the radiometries in the different bands, and those which dissociate the spectral from the spatial information. The P+XS method developed by CNES is part of the first class, and it will be considered as a reference thereafter. After a quick review of the existing methods, the ARSIS method (second class) will be developed and compared to P+XS.

Whichever merging method may be applied, the first mandatory step is the registration of P and XS images. This registration was performed using a classical control points technique in the following way:

- the P image is undersampled by a scale factor of 2, so that the pixel size is the same as the XS pixel size (20 m),
- using manually selected control points in P and XS images, a polynomial function is calculated to perform the geometrical transform between XS and P,
- the radiometry of each new XS pixel is obtained using a bicubic interpolation. The resampled image still has a 20 m resolution.

2. EXISTING MERGING METHODS

The first class of merging methods consists in combining the radiometries in the different bands (P, XS1, XS2, XS3) to synthetize the 10 m resolution multispectral image. Here are a few examples of such methods:

2.1. P+XS method[1]:

This method supposes that the P band is the spectral sum of XS1 and XS2 bands. Figure 1 shows how coarse is this approximation. The high spatial resolution multispectral images are called XP and are synthetized by the use of two equations:

$$L_{XP1} = 2\, L_P \frac{L_{XS1}}{L_{XS1} + L_{XS2}} \qquad L_{XP2} = 2\, L_P \frac{L_{XS2}}{L_{XS1} + L_{XS2}}$$

These two equations mean that all the existing structures in the P and XS2 images are introduced in the XP1 image, whatever their characteristic scales are. Hence, all the structures of characteristic scales greater than to 20 m are modified by the P and XS2 structures and the spectral content of XP1 differs from the spectral content of XS1. The same alteration occurs for XP2. Furthermore, this method does not provide means to derive a XP3 image, which is obtained in a bulk fashion by duplication of the XS3 image in line and column.

Munechika *et al.* [2] proposed a refined method based on the hypothesis that the P band is considered as a weighted sum of the XS bands. The coefficients are computed by a linear regression from the characteristic target for which the spectra is known. However, the same drawbacks for the modification of the structures are still present.

2.2. Component substitution methods:

The first step for all these methods consists in a duplication of the XS images in line and column to achieve a pixel-to-pixel registration with the P image. Let be the vectorial space defined by the three spectral bands XS1, XS2 and XS3. Axes transformation is achieved in such a way that one of the new axes represents an information close to the one of the P band, in accordance with a given criterion. Then, the projection of the XS images on this axis is replaced by the high resolution P image, before application of an inverse transformation giving back the three multispectral high resolution images. The criterion can be defined by a principal component analysis[3], by the Intensity-Hue-Saturation (I.H.S.) method[3, 5] or by others combinations of the XS images[4]. The major drawback of these methods is a modification of the spectral content of XS images. Indeed, each new multispectral high resolution image is obtained by the combination of the P image and of two components of the new reference which are in turn combinations of the three spectral bands. Hence, the four bands are mixed together and the spectral information in the multispectral high resolution images is not at all consistent with the original multispectral XS images.

The second class of merging methods is based on the separation of the spectral and the spatial informations. These methods extract some geometrical structures of the high resolution P image, to inject them in each multispectral XS image. Each multispectral high resolution image originates from a merging of the corresponding XS image and of the P image, but with no influence of the other spectral bands. With these methods, one can expect to simulate what a multispectral sensor will produce if with a 10 m spatial resolution.

2.3. High-pass filtering:

The high spatial resolution information from the P image is extracted by applying a high-pass filter. An image of the high spatial frequencies is produced. Then, this image is added pixel-to-pixel to the multispectral XS images[3]. The results of this method are highly dependent of the filter. Furthermore, the injection of high spatial frequencies by images addition suppresses all relationships between numerical value and radiance. The spectral content of the computed image is dramatically altered relatively to the XS images.

2.4. Pradines method:

Let consider each 20 m super-pixel X of XS images independently. Let divide this super-pixel in four pixels XPj of 10 m corresponding to four pixels Pj of the P image. If X represents the super-pixel of the given XS band, the radiometry of the XPj pixels is:

$$XP_j = X \cdot \frac{P_j}{P_1 + P_2 + P_3 + P_4} \qquad (j = 1, ..., 4)$$

This equation means that the radiometric sum of the XPj pixels is equal to the radiometry of the X super-pixel. Price[2] proposed a refined method, but the concept is the same. The major drawback of this method is that a high correlation between the P image and each XS image is needed. Furthermore, because each super-pixel is processed independently of its neighbours, the resulting image could be very noisy.

3. ARSIS METHOD

To obtain high resolution multispectral image from the initial XS images without degrading the spectral information, one must add only the missing structures which characteristic scales are between 10 and 20 m should be added. Two problems arise:

How to extract only these structures?

How to inject them in the original XS image and preserve the physical meaning of the radiometry?

The ARSIS method, by the use of the multiresolution analysis and of the wavelet transform, proposes a solution.

The multiresolution analysis (MRA) is a pyramidal algorithm which allows to compute successive approximations of an image with coarser and coarser spatial resolutions. The wavelet transform (WT) associated with the MRA, modelizes the difference of information existing between two successive approximations of a same image. With these tools, one can shrewdly study the characteristics scales of the phenomenons in the image[6, 7, 8]. The basis of the pyramid provided by a MRA is the original image.

Climbing in the pyramid is equivalent to compute coarser and coarser approximations of the initial image. The theoretical limit is the top of the pyramid composed of one pixel. The difference of information between two successive approximations is represented by wavelet coefficients images corresponding to the structures of this peculiar characteristics scales.
The P and XSi (i = 1, ..., 3) images are represented by two pyramids which spatial resolution of the basis differ by a factor of two, as shown in Figure 2.
The Mallat algorithm[7] is used to compute the successive approximations of the original images. The difference of information between each approximation is represented by three wavelet coefficients images describing the structures in diagonal, horizontal and vertical directions. The inverse operation corresponding to the MRA is called reconstruction and they both constitue an exact operation. This means that if a MRA and a reconstruction are applied to an image, the result is equal pixel-to-pixel to the initial image.
To obtain multispectral high resolution images, the ARSIS method extends the XS pyramid at a 10 m resolution with the help of the P pyramid. In this purpose, one can use the wavelet coefficients images corresponding to the P structures of characteristic scales 10-20 m to synthetize the wavelet coefficients images needed to reconstruct an XS image with a 10 m spatial resolution. But, these structures are closely related to the radiometric characteristics of the original P image, and it was not satisfying to directly associate them with the XS image. To compute the desired wavelet coefficients images, a model is established between the known wavelet coefficients images of the P and XS images at scales greater than 20 m, as shown Figure 3. This model may take into account the evolution of the information through the scales. By the means of the model and of the known wavelet coefficients images of the P image at scale 10-20 m, the desired wavelet coefficients images for the considered XS image at scale 10-20 m can be synthetized. An inverse wavelet transform or reconstruction is then applied to this synthetized wavelet coefficients images and the original XS image to obtain a multispectral high resolution XS-HR image. It is important to notice that by construction, the approximation at 20 m of the XS-HR image obtained by the ARSIS method is identical to the original XS image.
The mother wavelet used by the Mallat algorithm has to be orthogonal, to ensure the decorrelation of the structures to be introduced in the XSi pyramid. Also the structures should be as localized as possible. A wavelet of regularity two described by Daubechies[9], which is represented by a filter with four coefficients was selected.
The only hypothesis of the ARSIS method is that the wavelet coefficients images in the P and XS bands presents some similarity. The more its spectral band is overlapping P, the more meaningful the physical content of an XS-HR image. The XS3-HR image will present particular structures issued from the P band and usually invisible in the near infra-red spectra. However, any method designed to improve the spatial resolution of the XS3 image with the help of the P image meets this limitation.

4. XS-HR QUALITY ASSESSMENT

The ARSIS method was applied to a SPOT image of the region of Barcelona (Spain) presented Figure 4. To quantify the improvement due to the ARSIS method, the XS-HR images were compared to the XP images computed by the P+XS method. But the comparison of these two images to a reference is impossible. Indeed, multispectral XS image at the spatial resolution of 10 m are not available. Hence, the P and XS image were spatially degraded to a lower resolution of respectively 20 and 40 m. Then, XS* images were synthetized at the best resolution available (*i.e.* 20 m) and compared on a pixel basis to the original XS images. Table 1 presents some statistical results computed on the difference image, thus quantifying the efficiency of the ARSIS method.

	XS1		XS2		XS3	
	P+XS	ARSIS	P+XS	ARSIS	P+XS	ARSIS
Bias (ideal: 0) relatively to the mean of XS	0.38 0.7 %	0.00 0.0 %	0.28 0.6 %	0.00 0.0 %	0.03 0.1 %	0.00 0.0 %
VarianceXS* - actual variance (ideal: 0) relatively to the real variance	50 35 %	4 3 %	42 19 %	7 3 %	8 10 %	6 7 %
Entropy XS* - actual entropy (ideal: 0) relatively to the real entropy	0.145 3.6 %	0.013 0.3 %	0.077 1.8 %	0.013 0.3 %	- 0.053 - 1.4 %	- 0.036 - 0.9 %
Correlation coefficient between XS and XS* (ideal: 1)	0.97	0.99	0.98	0.99	0.86	0.95
Standard deviation of the differences (ideal: 0) relatively to the mean of XS	3.76 6.5 %	2.03 3.5 %	3.10 6.4 %	2.23 4.6 %	4.65 8.5 %	2.84 5.1 %

Table 1: statistics on the differences between XS and XS* (in radiance or relative value) for the images of the region of Barcelone (Spain)

The bias denotes a systematic error. The differences of the variances and of the entropies are representative of overall changes in of the information content. The correlation coefficient is an indicator of the global similitude of the XS* and XS images. The standard deviation of the differences image assesses the precision of the estimation on a pixel basis. For all the criterias, the ARSIS method gives better results than the P+XS method. This is due to the fact that the ARSIS method only introduces the small structures without modifying the original XS content. The diminution of the entropy in the XS3 band for the P+XS method is due to the fact that the coarser XS3 image at 40 m contains less information than the original one and the XS3* image which is obtained by duplication of the 40 m image[1], too. For the ARSIS method this diminution of the entropy is certainly due to the local anti-correlations existing between the XS3 and P spectral contents. A model taking into account these anti-correlations will certainly improve these results in the XS3 case.
Table 2. shows the probability to have in one pixel, a relative error, in absolute value, less than a given threshold.

	XS1		XS2		XS3	
Thresholds (%)	P + XS	ARSIS	P + XS	ARSIS	P + XS	ARSIS
0.001	8.8	25.3	11.4	23.0	8.8	15.2
0.1	8.8	25.3	11.4	23.0	8.8	15.2
1	9.2	26.1	11.7	23.5	9	15.4
2	26.6	59.5	26.0	42.7	25.8	41.6
5	57.7	89.5	60.0	81.5	54	74.9
10	90.3	98.9	91.1	97.2	81.3	94.3
20	99.6	100	99.7	99.9	96.8	99.5
50	100	100	100	100	99.9	100
100	100	100	100	100	100	100

Table 2: probability (in %) to have in one pixel a relative error (in absolute value and in %) less than or equal to the indicated thresholds, for the image presented Figure 4.
The ideal value is 100 for the 0.001 % threshold.

The results of table 2 show that for the ARSIS method almost all the pixels have a relative error inferior to 10 %. The percentage of pixels with a null error (less than 0.001 %) is always greater than 15 %.
Figure 5. is a example of visual differences existing between both methods.

5. CONCLUSION

The results (Tables 1 and 2) show the quality of the image obtain by the ARSIS method. The resulting images are available for applications which need high spatial and spectral resolutions. Hence, this method is relevant for the future SPOT satellites. The same technique has been applied to the case of Thematic Mapper sensor of the Landsat satellite with encouraging results.
The wavelet transform and the multiresolution analysis have brought dramatic improvement of the results. The quality of the above results can be enhanced by the use of $\sqrt{2}$ algorithm[10] and adaptive models of transformation of the wavelet coefficients images.

6. REFERENCES

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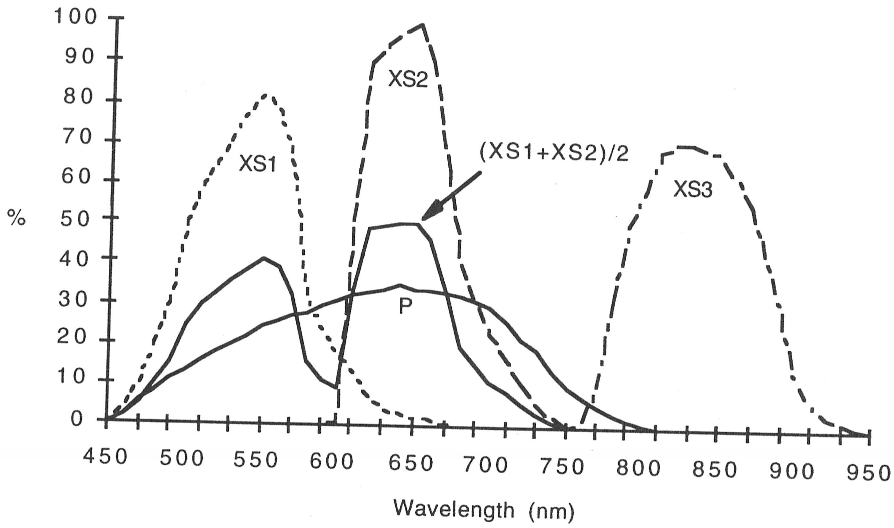


Figure 1: spectral bands of SPOT

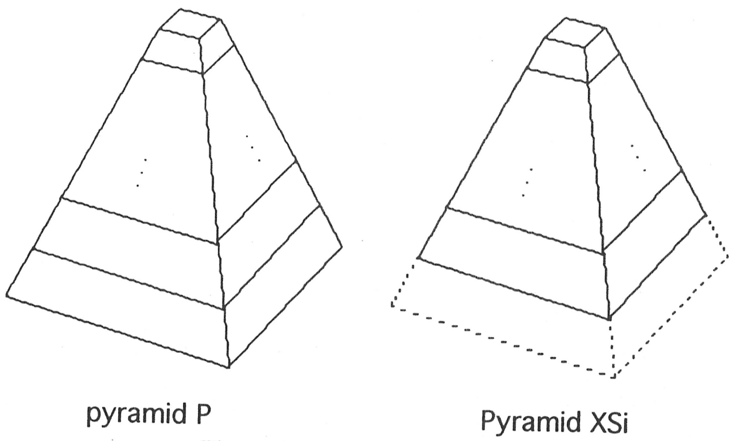


Figure 2: multiresolution pyramids

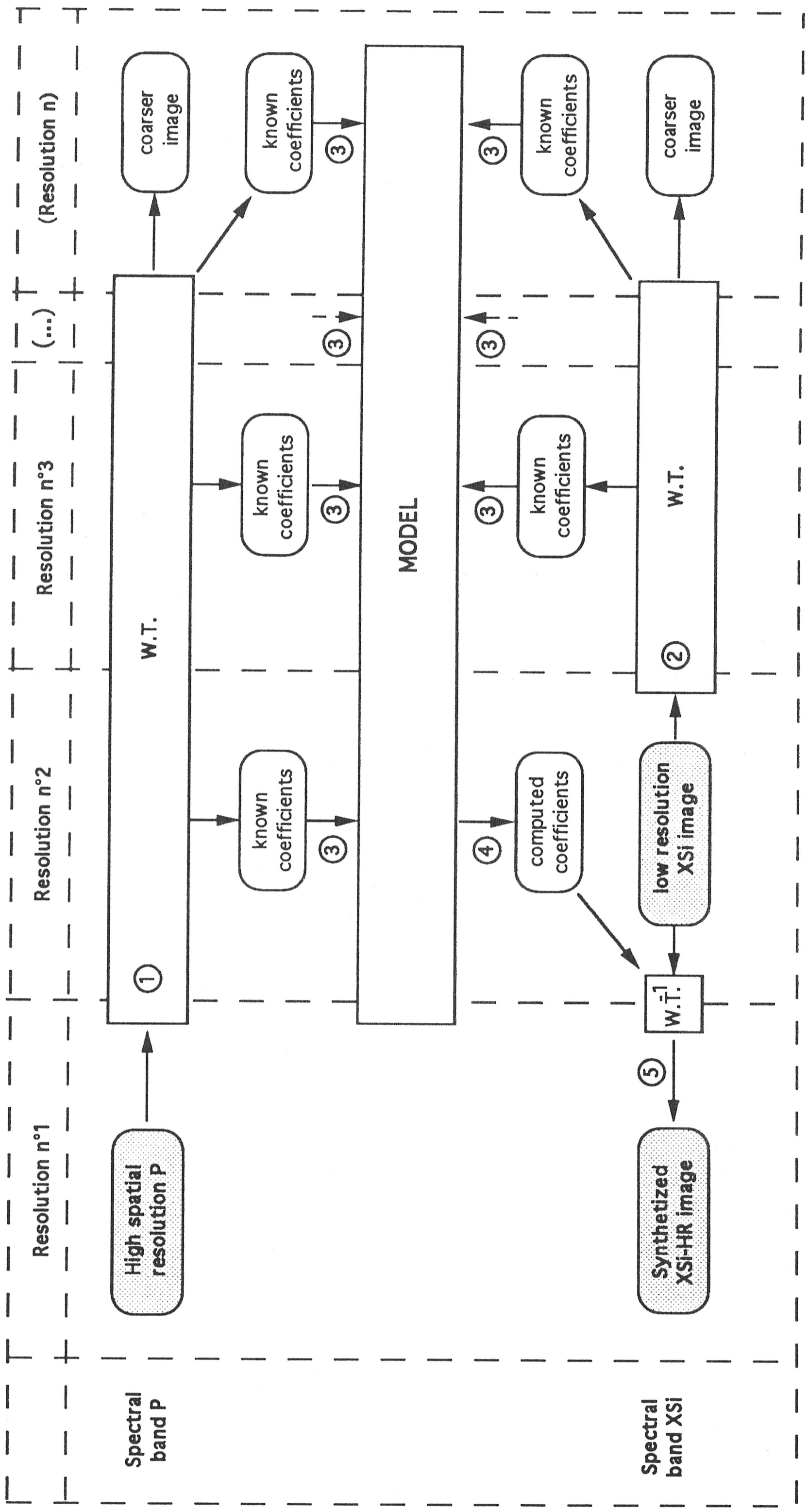


Figure 3: Principle of the ARSIS method

Figure 4: original panchromatic (P) image from the region of Barcelona (Spain).

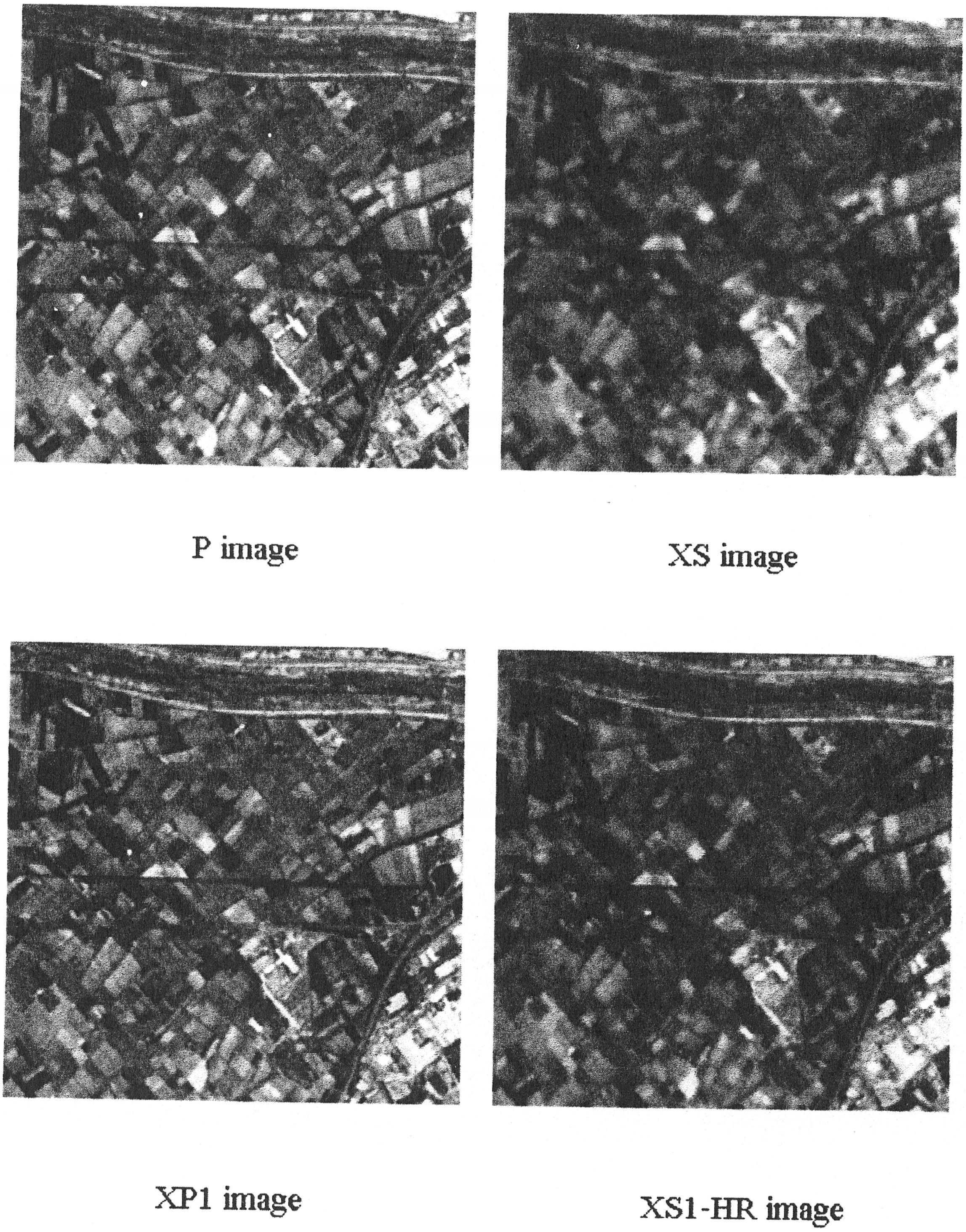
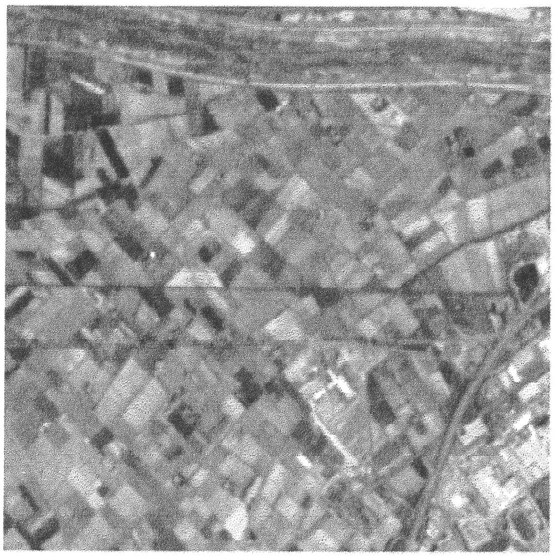
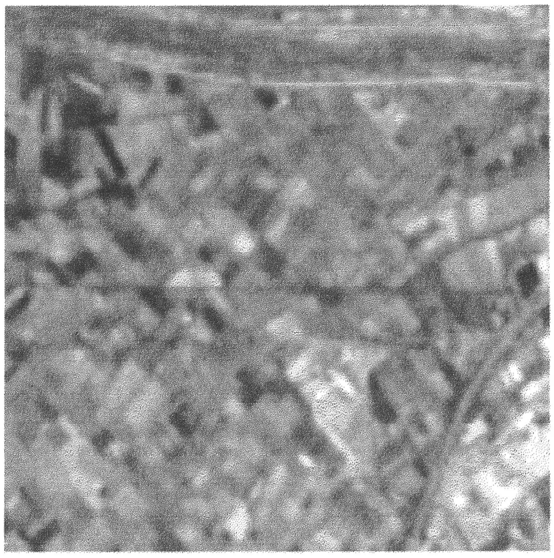


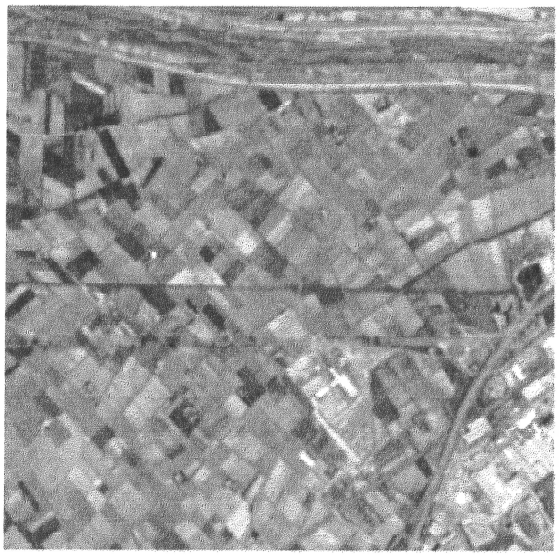
Figure 5: Examples of original images and results



P image



XS image



XP1 image

XS1-HR image

Figure 5: Examples of original images and results